Evaluation of a Semi-Automatic Algorithm for Tracking Tricuspid Valve Annulus on Magnetic Resonance Images

Francesco Maffessanti[1,2], Paola Gripari[2], Gianluca Pontone[2], Daniele Andreini[2], Maria C Carminati[1], Mauro Pepi[2], Enrico G Caiani[1]

[1]Biomedical Eng. Dpt, Politecnico di Milano, Milan, Italy
[2]Centro Cardiologico Monzino IRCSS, Milan, Italy

Abstract

Despite cardiac magnetic resonance (CMR) is the reference imaging technique for the evaluation of ventricular function, its use for the assessment of tricuspid valve is still minimal.

Tricuspid annulus (TA) evaluation in 3D is feasible from CMR when performed in rotational long-axis. However, this process is based on manual identification of TA reference points. Our aim was to test the accuracy of semi-automated algorithm, based on normalized cross-correlation, in order to reduce the cumbersome manual identification frame-by-frame.

Analysis was performed on 10 healthy volunteers, and an expert reader visually inspected and classified as correct or not the TA points position. The proposed algorithm, showed accuracy equal to 87%, demonstrating its applicability to obtain the dynamic 3D morphology of TA, with potential benefits in growing the understanding of tricuspid valve, and therefore in patient.

1. Introduction

Tricuspid valve morphology, together with other functional parameters including right and left ventricular size and shape, and pulmonary artery pressure, is known to be an important factor conditioning the patient outcome after cardiac surgery, even when relevant to left heart pathology. In particular, significant tricuspid regurgitation has been shown to be associated with poor prognosis after mitral valve surgery or plasty [1,2]. Despite these evidences, the comprehension of the underlying mechanisms is still limited, mainly by the fact that the understanding of tricuspid valve physiology is still incomplete, leading to recently referring to the tricuspid valve as the forgotten valve [3].

The deep knowledge of tricuspid valve morphology has been hampered by the unavailability of reliable measurements relevant to the valve itself. Indeed, the use of 2D echocardiography is able to quantify information relevant to diameters only. More recently, few studies have shown the possibility to obtain, using real-time 3D echocardiography, more accurate and reliable measurements regarding tricuspid annulus (TA) area, perimeter, main diameters, as well as leaflet tethering, and to associate these measurements to the development of residual tricuspid regurgitation after TA annuloplasty [4,5]. However, trans-thoracic echocardiography may result in suboptimal image quality, while imaging the tricuspid valve is not always feasible using trans-esophageal probe.

Despite cardiac magnetic resonance (CMR) imaging is the reference techniques for the evaluation of left and right ventricular volumes and function, as well as regurgitation, its use for the assessment of valve morphology is still limited, because of its intrinsical 2D nature. We recently proposed a method for the 3D quantitative evaluation of mitral annulus, based on multiple rotational long axis acquisitions, followed by manual selection of reference points and reconstruction of valvular annulus in the 3D space [6].

Our aim was to adapt and apply the previously developed approach to the TA, and to develop and test the accuracy of a semi-automated tracking algorithm for the TA, in order to reduce the cumbersome frame-by-frame manual identification.

2. Methods

2.1. Population

A group of 10 healthy volunteers (8 male, 2 female; mean age 35±16 years) was considered for analysis. Exclusion criteria were standard contraindications to magnetic resonance imaging. All subjects were enrolled at the Centro Cardiologico Monzino IRCCS, Milan.

2.2. Cardiac magnetic resonance

CMR images were obtained using a 1.5 T Signa Excite (GE Medical Systems) system with a phased-array

Figure 1. A) schematic representation of the CMR rotational long-axis images in the 3D space; B) screenshot of the user interface udes to manually identify the TA reference points (green dots) in each plane at ES and ES; C) the reference points in the 3D space, together with the fitted TA.

cardiac coil. Steady state free precession (SSFP) cine images were acquired in 18 long-axis planes, evenly rotated every 10 degrees along the axis ideally passing through the centre of the TA (spatial resolution: 0.74 mm; slice thickness: 6 mm; matrix: 512x512), as shown in Figure 1.A.

Each acquired plane included 20 phases over the cardiac cycle during 10-15 seconds breath holds, with different temporal resolution according to the RR interval of each subject, resulting in a total of 360 images for each acquisition. Images were exported in the standard DICOM format.

2.3. Data analysis

Dedicated custom software (Figure 1.B) was used to quantitatively describe TA morphology and cinematic, by means of adapting a previous tool for the analysis of the mitral annulus [6] developed in the Matlab environment (Mathworks Inc).

Briefly, in each of the acquired 18 planes, the position of the two TA points was manually identified by an expert cardiologist (Figure 1.B, green dots), both at end-diastole (ED) and end-systole (ES). Moreover, the image plane showing the RV inflow and outflow tracts, as well as the cross-sectional view of the ascending aorta was selected by the operator, to be used as a consistent anatomic reference to identify different regions on the TA.

The manually identified TA points were then automatically tracked frame by frame throughout the cardiac cycle using an algorithm based on normalized cross-correlation [7].

First, a feature t, centered in each initialized points was considered in the frame i; a region of search f, larger than t, was defined in both the previous and the following frames, i-1 and i+1, respectively.

The normalized cross-correlation coefficient between the feature matrix *t* relevant to the frame *i* and the image *f* relevant to the frame *i+1* closely follows the formula:

$$\gamma_{i,i+1}(u,v)=\frac{\sum_{x,y}\left[f_{i+1}(x,y)-\bar{f}_{i+1}(u,v)\right]\left[t_i(x-u,y-v)-\bar{t}_i\right]}{\sqrt{\sum_{x,y}\left[f_{i+1}(x,y)-\bar{f}_{i+1}(u,v)\right]^2\sum_{x,y}\left[t_i(x-u,y-v)-\bar{t}_i\right]^2}}$$

where the sum is over x,y under the window containing the feature t positioned in (u,v), $\bar{t}$ is the mean of the feature, and $\bar{f}_{u,v}$ is the mean of f(x,y) under the feature.

The position of the feature in the frame i+1 was estimated as the location of the maximum of the coefficient matrix $\gamma_{i,i+1}$ (Figure 2). The position of t was estimated till the following initialization frame (i.e., from ED to ES, and from ES to ED).

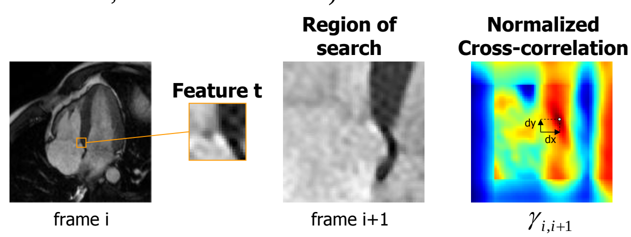

Figure 2. Schematic representation of the algorithm for TA points tracking based on normalized cross-correlation. The displacement of the reference feature t, centered on the a manually initialized TA point, was estimated as the position of the maximum of the normalized cross-correlation (right, white dot) matrix between the feature t (left) and a region of search (mid) centered in the TA point position in one adjacent frame. See text for details.

The same procedure was performed backward, estimating the position of t in the previous frame as the location of the maximum of the matrix $\gamma_{i,i-1}$.

Therefore, for the generic frame j, two candidate positions for the feature t were obtained applying the forward and the backward algorithm, $p_j^+(u,v)$ and $p_j^-(u,v)$ respectively:

Finally, the position $p_j(x,y)$ of the TA point in the frame j was calculated as the weighted average between the two estimates obtained applying the algorithm forward and backward, $p_j^+(x,y)$ and $p_j^-(x,y)$, respectively:

$$p_j(u,v) = w_j^+ \cdot p_j^+(u,v) + w_j^- \cdot p_j^-(u.v)$$

where the weights w^+ and w^- ranges linearly between 1, in correspondence of the initialization frame from which the algorithm starts, and 0, in correspondence of the frame the algorithm stops. Therefore, this weighted average weights more the estimate closer to the starting point.

Tracking was performed using square features, 10 pixels width, centered in the TA point. Moreover, to speed up the algorithm, normalized cross correlation was evaluated for regions of search of 20 pixels width, surrounding the feature in the adjacent frames.

Once the position of TA points was obtained in each plane and frame, the identified TA points were transformed in the 3D space using the information stored in the appropriate DICOM fields. The TA 3D model was then automatically reconstructed by fitting the cloud of reference points using a 5th order Fourier approximating function (Figure 1.C).

From the 3D model, several parameters were computed: projected area, perimeter, the two main diameters, and height (Figure 3). The TA cinematic was assessed by considering the TA peak systolic excursion (TAPSE), of the three regions in which the TA was subdivided (anterior, posterior and septal region).

To validate the performance of the automated tracking, an expert reader visually inspected each frame and judged as appropriate or not the TA points position. Accuracy was then computed.

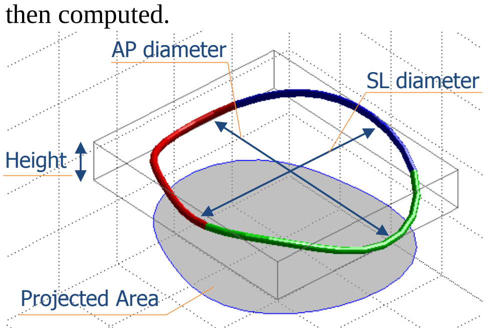

Figure 3. Schematic of obtained TA parameters: 2D projected area, TA height, antero-posterior (AP) and septo-lateral (SL) diameters. TA was subdivided in septal (blue), anterior (red) and posterior (green) regions.

3. Results

Analysis was feasible in all datasets, and took about 3 minutes for each subject. The position of the tracked TA points was visually judged as correct in 3122 out of 3600 (10 subjects, 360 images per subject) images, resulting in a total accuracy equal to 87%.

Figure 4 shows an example of temporal evolution of the considered parameters in a representative volunteer.

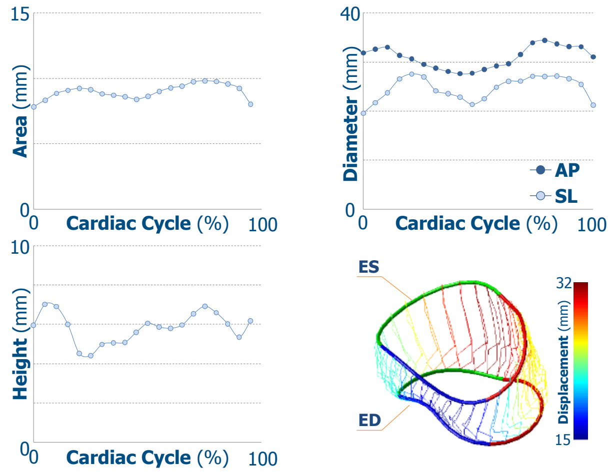

Figure 4. From top to bottom, left to right: changes in TA area, diameters (AP = antero posterior, SL = septo-lateral) and height, as well as the 3D recinstruction of TA at end-diastole (ED) and end-systole (ES). Lines represent the local trajectory of the TA throughout the cardiac cycle, color coded for the longitudinal displacement.

The cumulative results from the ten subjects are listed in Table 1.

Table 1. Tricuspid annulus (TA) measurement obtained at end-systole (ES) and end-diastole (ED). AP = antero-posterior; SL = septo-lateral; TAPSE = tricuspid annulus peak systolic excursion

TA measurement	ED	ES
Area (cm^2)	10.2±2.0	10.2±2.1
Perimeter (cm)	12.1±1.2	11.9±1.2
AP diameter (mm)	37.1±2.7	36.6±6.6
SL diameter (mm)	28.6±4.2	27.7±6.6
TAPSE (mm)		
global	19.1±5.2	
anterior	19.3±5.8	
posterior	21.3±3.4	
septal	16.3±4.9	

Our results were similar to those available in literature. In particular, AP and SL diameters, as well as area, were similar to those obtained at mid-systole by Ton-Nu et al [4] (AP = 34.0±5.0mm; SL = 26.0±3.6mm; Area = 9.7±2.1cm^2) in a group of 20 subjects with normal tricuspid valve.

Interestingly, compared to our results, those reported by Min et al [5] and relevant group of 59 patients with severe tricuspid regurgitation, showed similar values for AP (34.0±5.0mm), and an increase in the SL direction (30.9±5.0mm). This is in agreement with the fact that TA dilation is possible only with regard to the SL direction, corresponding to the free wall of the right ventricle [10].

The mean perimeter we found is consistent with those measured on 50 explanted normal TA by Silver et al [8] (perimeter = 11.4±1.1cm on men, 10.8±1.3cm on women), while posterior TAPSE is comparable to the data we reported in a group of 260 healthy volunteers by mean of M-mode echocardiography examination [9] (TAPSE = 24±3 mm). Moreover, we were able to demonstrate the significant difference on TA regional dynamic, as showed by a significantly higher TAPSE in the posterior region compared to the values measured in the anterior or septal portion of TA ($p<.05$, ANOVA). Conversely, the minimum displacement was found in the septal region.

4. Discussion

This study demonstrated the feasibility of the proposed approach, based on rotational CMR long-axis images acquisition, automatic tracking of the manually initialized reference points and reconstruction of the TA in the 3D space.

The relative small size of the study population did not allow to deeply investigate the physiologic dynamic behavior of the TA. Further studies, with a greater number of subjects are needed for this purpose.

Normalized cross-correlation is not the ideal approach to feature tracking as this technique is not invariant with respect to image scaling, rotation and translation. Nevertheless, the fact that breath holding is needed to acquire CMR images allows to overcome those limitations.

This approach could constitute the basis for in-depth evaluation of the TA by CMR; this, in conjunction with left and right ventricular volume and function obtained during the same examination, could improve the understanding of the mechanism leading to tricuspid valve regurgitation, with potential benefits in patient selection for tricuspid surgery concomitant to left heart valve repair.

References

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Address for correspondence.

Francesco Maffessanti, PhD
Department of Biomedical Engineering, Politecnico di Milano,
Piazza L. da Vinci 32,
20133 Milano, Italy.
Email: francesco.maffessanti@mail.polimi.it